

# Neutrino Oscillations as a Probe of Dark Energy

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(Dated: February 1, 2008)

We consider a class of theories in which neutrino masses depend significantly on environment, as a result of interactions with the dark sector. Such theories of mass varying neutrinos (MaVaNs) were recently introduced to explain the origin of the cosmological dark energy density and why its magnitude is apparently coincidental with that of neutrino mass splittings. In this Letter we argue that in such theories neutrinos can exhibit different masses in matter and in vacuum, dramatically affecting neutrino oscillations. Both long and short baseline experiments are essential to test for these interactions. As an example of modifications to the standard picture, we consider simple models which may simultaneously account for the LSND anomaly, KamLAND, K2K and studies of solar and atmospheric neutrinos, while providing motivation to continue to search for neutrino oscillations in short baseline experiments such as BoONE.

## I. INTRODUCTION AND MOTIVATION

In the past decade, two of the greatest advances in physics have been the experimental confirmation of neutrino oscillations, and the observation of acceleration of the cosmological expansion from a mysterious dark sector. In this letter, we link the two, discussing how neutrino oscillation experiments could reveal non-gravitational interactions between matter and the dark sector.

In recent years great progress has been made in understanding neutrino masses and oscillations. As first pointed out by Wolfenstein[1], and Mikheev and Smirnov [2, 3] the forward scattering of neutrinos by matter via the weak interactions, while having a very small cross section, can have a significant effect on neutrino oscillations. As a consequence, in all theoretical analyses of the oscillations of neutrinos passing through the sun or earth, matter effects on neutrino propagation have played a central role. The plethora of neutrino mass experiments [4, 5, 6, 7, 8, 9, 10] appearing in the wake of the original Homestake [11] solar neutrino experiment have converged to a consistent picture of neutrino mass: large angle MSW explaining the solar deficit, and a large mixing angle explaining the atmospheric neutrino deficit as well. In spite of this convergence, very little is really known about the interactions and properties of neutrinos. Aside from mild constraints from BBN and supernovae, interactions of low energy neutrinos with themselves or with ordinary matter are poorly known. Given that we already know that neutrino masses have tremendous en-

vironmental dependence even with purely weak interactions, and given our experimental ignorance of neutrino interactions, we must ask whether new interactions could offer additional medium dependence, and what physics such new interactions could probe.

A natural origin for new interactions would be the sector responsible for dark energy. Neutrinos and neutrino oscillations are ideal windows into the dark sector, not only because the neutrino's known interactions are weak, and masses small, but also because if lepton number is broken, neutrinos carry no conserved charges and are uniquely capable of mixing with fermions in the dark sector. The dark energy offers an important clue, in that its scale -  $(2 \times 10^{-3} \text{eV})^4$  - is comparable to the scale of neutrino mass splittings,  $\delta m_\nu^2 \sim (10^{-2} \text{eV})^2$ . Should there be new particles at this scale, their interactions and mixings with neutrinos could be significant. Given that neutrino masses are already known to be sensitive to Planck-suppressed interactions via the seesaw mechanism [12, 13], it is not at all surprising to suggest that new, sub-gravitational forces mediated by the dark sector particles could generate additional medium dependence of the neutrino mass.

Here we broaden the discussion of a class of theories first proposed in ref. [14] to explain the nature of the dark energy. These theories explain the similarity between the dark energy scale and the measured scale of neutrino mass splittings, by postulating that neutrino masses are variable, depending on the value of a scalar field  $\mathcal{A}$ . The potential for  $\mathcal{A}$  is taken to be very flat, so that the magnitude of  $\mathcal{A}$  depends upon the cosmological density of neutrinos. As a result, these mass varying neutrinos (MaVaNs) become heavier as their density decreases, and the total energy of the fluid (both in neutrinos and in the  $\mathcal{A}$  field), identified with the dark energy, can vary slowly as the neutrino density decreases. Not only can this explain the origin of dark energy, but it can

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also substantially alter the cosmological limits on neutrino mass [14], modify neutrino mass relationships to leptogenesis [15], and change the flavor content of the cosmic background neutrinos and distant astrophysical sources [16].

Here we show that sub-gravitational strength interactions between ordinary matter and the  $\mathcal{A}$  field naturally occur, and can cause the value of  $\mathcal{A}$  to differ in the presence of matter from its vacuum value. This leads to medium-dependent neutrino masses and novel features in neutrino oscillations. Observing these effects would not only extend our understanding of neutrinos, but would also shed light on the mysterious dark sector which governs the evolution of the universe on the grandest scales.

After explaining in the next section how such effects arise, we proceed in III to consider how these matter effects can improve agreement between the LSND results and other experiments.

## II. DARK BOSONS, DARK FERMIONS AND THE STANDARD MODEL

For all we know there could be a profusion of new particles with no standard model gauge interactions. We will refer to such particles as “dark”. The main constraint on such indiscernible beasts comes from cosmology—the success of Big Bang nucleosynthesis (BBN) strongly suggests that the only relativistic species in thermal equilibrium with visible matter at a temperature of order an MeV are those we already know about. Thus dark particles must either be much heavier than an MeV or too weakly interacting to thermally equilibrate with visible matter in the early universe when the temperature was a few MeV. Such considerations have been used to place limits on neutrino mixing with sterile neutrinos [17, 18] and on other interactions with light dark particles. Dark particles are also constrained from the requirement that they not excessively contribute to supernovae cooling. In ref. [14], however, it was shown that significant neutrino-dark fermion mixing today can be reconciled with BBN and supernova cooling constraints, due to the strong medium dependence of neutrino properties for MaVaNs.

In this section we will explore the potential impact of the dark sector on neutrino oscillations. We consider a dark sector consisting of a scalar,  $\mathcal{A}$ , and fermions,  $n$ . We will take the dark energy scale,  $\sim 2 \times 10^{-3}\text{eV}$  to be the typical mass scale of this sector. Taking a cue from the standard model, where masses range over nearly six orders of magnitude for the charged fermions, we consider mass parameters within a few orders of magnitude of the dark energy scale, but not, *e.g.*, Hubble sized Compton wavelengths as in quintessence models.

A general Lagrangian for the dark sector includes

$$\delta\mathcal{L} = -m_n(\mathcal{A})nn - V_0(\mathcal{A}), \quad (1)$$

where we ignore operators involving more than two fermions, which are irrelevant to our discussion. The

Majorana mass  $m_n(\mathcal{A})$  may be linear in  $\mathcal{A}$ , or some more complicated function. The only renormalizable interaction allowed between the dark sector and the standard model is  $y_\nu h \ell n$ , where  $y_\nu$  is the Yukawa coupling of the Higgs boson to a SM neutrino and a dark fermion. This interaction yields a Dirac mass  $m_D = y_\nu v$ . If the dark fermion Majorana mass is well below the weak scale,  $y_\nu$  must be extremely small. Many simple mechanisms for extremely small Yukawa couplings exist in the literature, for example, see [19]. If  $m_n(\mathcal{A}) > m_D$  then the see-saw mechanism yields an effective  $\mathcal{A}$ -dependent neutrino mass,  $m_\nu(\mathcal{A}) = m_D^2/m_n(\mathcal{A})$ . We also assume there may be other contributions to the neutrino mass, *e.g.* from a GUT-seesaw mechanism, which are  $\mathcal{A}$  independent.

As in [14] the energy density of the cosmic background neutrinos will tend to drive  $m_\nu$  to smaller values and, consequently,  $m_n$  to larger values. That is, the effective neutrino mass is a function of the background neutrino density. The neutrinos also have an effective coupling to  $\mathcal{A}$  with strength  $\lambda_\nu = \partial m_\nu / \partial \mathcal{A}|_{\langle \mathcal{A} \rangle}$ .

For a nonrelativistic neutrino background, we can find the value of  $\mathcal{A}$  by minimizing the effective potential

$$V(\mathcal{A}) = n_\nu m_\nu(\mathcal{A}) + V_0(\mathcal{A}) \quad (2)$$

where  $V_0$  is the effective potential in vacuum.

Up to this point, we have not considered the possible interactions of  $\mathcal{A}$  with other matter. To begin, we consider couplings radiatively generated from SM loops. There are a number of possibilities to consider. The most potentially significant are corrections to the electron wave function renormalization (and hence to the electron mass) from W and Higgs loops, and to the Z-propagator (and hence to quark masses at higher loop). If we consider the theory to contain just the standard model with variable ( $\mathcal{A}$ -dependent) masses, these corrections also appear to depend on  $\mathcal{A}$ , at order  $G_f m_\nu^2$ . In matter with density of  $3g/\text{cm}^3$ , such an interaction has a comparable effect on the  $\mathcal{A}$  potential as the cosmic neutrino background, with the vastly higher density of electrons compensating for the much weaker coupling.

However, the electroweak radiative corrections are dominated by high ( $\sim M_W$ ) momenta, so if the  $n$  fermions are lighter than  $M_W$ , they should also be considered in the loops. A careful treatment finds that the leading corrections in this case are proportional to  $G_f m_D^2$ , and independent of  $\mathcal{A}$ . Terms depending on  $\mathcal{A}$  are suppressed by an additional factor of  $G_f m_n^2(\mathcal{A})$  and are too weak to be relevant. We conclude that radiatively generated couplings of the dark scalar to quarks and charged leptons are not interesting if (and only if) the scalar-neutrino interaction arises solely due to neutrino mixing with a dark fermion which is much lighter than the W boson.

We also consider non-renormalizable operators which couple the dark scalar to visible matter, such as might arise from quantum gravity. At low energies, these interactions would be appear as Yukawa couplings of  $\mathcal{A}$  to the proton, neutron and electron, which we parametrize

as  $\lambda_i m_i / M_{\text{Pl}}$ , with  $i = p, n, e$ , respectively, and where  $M_{\text{Pl}}$  is the Planck scale. Couplings  $\lambda_{n,p} \lesssim 10^{-2}$  are consistent with tests of the gravitational inverse square law for an  $\mathcal{A}$  mass larger than  $\sim 10^{-11} \text{eV}$  [20], and, (for  $\lambda_p \sim \lambda_n$ ), with tests of the equivalence principle for an  $\mathcal{A}$  mass larger than  $\sim 10^{-8} \text{eV}$  [21, 22].

In the presence of matter, and ignoring the electron contribution, we have a new effective potential for  $\mathcal{A}$

$$\bar{V} = \frac{\lambda_B \rho_B \mathcal{A}}{M_{\text{Pl}}} + V(\mathcal{A}), \quad (3)$$

where  $\rho_B$  is the mass density of baryonic matter, and we have set  $\lambda_p = \lambda_n = \lambda_B$ .

The change in the neutrino mass in the presence of matter may be estimated to be

$$\Delta m_\nu \sim 1 \text{eV} \left( \frac{\lambda_\nu}{10^{-1}} \right) \left( \frac{\lambda_B}{10^{-2}} \right) \left( \frac{\rho_B}{\bar{\rho}_B} \right) \left( \frac{10^{-6} \text{eV}}{m_{\mathcal{A}}} \right)^2 \quad (4)$$

where  $m_{\mathcal{A}}^2 \equiv V''(\mathcal{A})$ , and  $\bar{\rho}_B = 3 \text{g/cm}^3$ , a baryon mass density which is typical of the earth's crust. This estimate assumes the shift in  $\mathcal{A}$  is sufficiently small to allow for a Taylor expansion of  $V$  about the present epoch background value for  $\mathcal{A}$ ; for a flatter potential, as was used in [14] in order to explain dark energy, the change in the neutrino mass will be much larger, and the  $\mathcal{A}$  mass will be variable.

The generic point is that for MaVaNs, the neutrino mass is environment dependent, and the neutrino mass in rock or in a star can vary considerably from the neutrino mass in air and in space. Significant matter effects on neutrino propagation are familiar, as in the Standard Model MSW mechanism. The possibility of such medium dependence was noted early by Wolfenstein [1], and a scenario where Dirac neutrinos only have mass in matter has been considered previously [23]. New scalar contributions to the effective neutrino mass can be distinguished experimentally from standard MSW contributions and from new vector contributions [24, 25, 26, 27, 28, 29, 30, 31] as they are energy independent, and equal for neutrinos and antineutrinos, absent CP violation.

### III. MATTER EFFECTS IN EXISTING EXPERIMENTS

Since dark energy now provides us a motivation to consider the possibility of medium dependent neutrino mass, we want to examine what the effects could be on existing neutrino data. In particular it is instructive to examine the LSND evidence for short baseline  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations in light of these possible matter effects. Here, we will study whether the ability to have different  $\delta m^2$ 's in air and matter can lead to an improved agreement both between the other positive results as well as the existing negative results.

Let us begin by discussing the relevant experiments. We can loosely group oscillation experiments into three

categories. There are long baseline experiments (LBL), which includes solar neutrino experiments, KamLAND, K2K, and SuperK as well as earlier studies of atmospheric neutrinos. These experiments have all seen evidence for neutrino oscillations, and involve significant propagation through dense matter. The positive results are interpreted through neutrino oscillations to require two small mass squared splittings,  $\mathcal{O}(8 \times 10^{-5} \text{eV}^2)$  for the solar neutrinos and KamLAND, and  $\mathcal{O}(2 \times 10^{-3} \text{eV}^2)$  for K2K and atmospheric neutrino studies. The Super-K atmospheric results should not entirely be classified as positive as the through-going muon data show no evidence for oscillation. This result relies on a knowledge of very high ( $\mathcal{O}(100 \text{ GeV})$ ) neutrinos and may be subject to systematics not present in e.g., the angular dependence of the multi-GeV events. There are null short baseline experiments (NSBL), including the CHOOZ, Bugey, and Palo Verde reactor experiments, and the higher energy CDHS, KARMEN, CHORUS, and NOMAD experiments, involving muon neutrinos. These experiments have all seen no evidence for neutrino oscillations. Lastly, there is LSND, whose results are consistent with oscillations with a mass splitting greater than  $3 \times 10^{-2} \text{eV}^2$ . These results are summarized in [32].

Because three neutrinos can only accommodate two independent mass splittings, LSND has generally been interpreted to necessitate an additional sterile neutrino or neutrinos. However, recent studies (see [33] and references therein) demonstrate that this, too, gives a poor fit to the data. Incorporating LSND by invoking CPT violation seems in conflict with recent KamLAND data, while a 3+2 sterile scenario [34] improves the fit in a seemingly contrived way by setting the masses of the sterile neutrinos to lie in regions where the NSBL constraints are weakest.

Four neutrino scenarios have a poor fit due in large part to the differences in how neutrino oscillations affect disappearance experiments compared with the positive appearance signal at LSND. Atmospheric and solar neutrino data are inconsistent with a large mixing angle of  $\nu_e$  and  $\nu_\mu$  with any sterile neutrino, implying that the mass eigenstates associated with solar and atmospheric oscillations are almost entirely active. Thus in a four neutrino scenario, the mass eigenstate associated with the LSND mass squared difference must be mostly sterile, with small admixture of  $\nu_e$  and  $\nu_\mu$ . With these constraints, the amplitude for the LSND  $\nu_\mu \rightarrow \nu_e$  transition is the product of two small mixings (the component of the heavy eigenstate which is  $\nu_\mu$  and the component which is  $\nu_e$ ), while only one small mixing angle appears in the SBL disappearance experiments (the component which is  $\nu_e$  for reactor experiments). Put another way, LSND is only sensitive to  $\nu_\mu \rightarrow \nu_e$ , while disappearance experiments are sensitive to  $\nu_e \rightarrow \nu_\mu$  as well as  $\nu_e \rightarrow \nu_s$ , which is, in general, larger.

The experimental limits of exotic matter effects on neutrino oscillations have barely been explored. Here we will see to what extent matter effects can improve agree-

ment of LSND with other experiments. Of the NSBL experiments, the Bugey experiment involves dominantly propagation through air [35, 36]. The Palo Verde results involve neutrinos dominantly propagating through earth [37]. The CHOOZ experiment neutrinos propagate roughly 10-20% through earth [39]. Of the terrestrial positive signal experiments, both KamLAND and Super-K study the propagation of neutrinos through earth.

Within the context of purely three neutrino oscillations, one might want to consider what the limits are on the  $\delta m^2$ 's and mixing angles in air and earth separately. The possibility that LSND is testing the “air” values of the neutrino mass matrix seem excluded by the fact that KARMEN has similar air pathlength as LSND, and hence would constrain such an oscillation scenario more strongly than ordinary neutrino oscillations.

If one wants to understand the LSND signal from a “matter” value for the neutrino mass matrix, there are a number of experiments to consider. KamLAND gives evidence for large mixing of  $\nu_e$  with some other neutrino in earth with a mass splitting  $5 \times 10^{-5} \text{eV}^2 \leq \delta m^2 \leq 10^{-3} \text{eV}^2$  where the upper bound comes from CHOOZ and Palo Verde. Super-K atmospheric and K2K show evidence for  $\nu_\mu$  mixing significantly with  $\nu_\tau$  and a mass splitting  $\delta m^2 \geq 10^{-3} \text{eV}^2$ . In fact, the strongest evidence for the scale of the mass splitting comes from the zenith-angle dependence of the multi-GeV events. In this scenario, one has the exciting possibility that the presently quoted value of mass splitting for atmospheric neutrinos is merely an artifact of the significant depletion of those neutrinos originating below the horizon, which could arise in this scenario from a much larger mass splitting in matter. This speculation, however, seems at odds with the through-going muons, which, together with the stopping muons, give an upper bound on the scale of oscillations of about  $10^{-2} \text{eV}^2$  [38].

These results would suggest that using only three neutrinos, one cannot reconcile LSND with the other experiments. However, should there be some systematic effect in the  $O(100 \text{ GeV})$  neutrinos, or if some unknown process contributes to the production of high energy atmospheric neutrinos, one can consider a scenario where  $(\nu_\mu + \nu_\tau)/\sqrt{2}$  has a larger mass in matter in order to explain the LSND result, and a mass  $\sim 3 \times 10^{-2} \text{eV}$  in air to explain the atmospheric result. Leaving the lightest two mass eigenstates to be essentially constant in air and matter, and a small admixture of  $\nu_e$  in the heaviest, it appears that the matter parameters of  $0.07 \text{eV}^2 \leq \Delta m^2 \leq 0.26 \text{eV}^2$ , and  $0.02 \lesssim \sin^2 2\theta \lesssim 0.12$  appears to fit all of the results outside of the throughgoing muons. (The range in the mixing angle could in fact be much larger, depending on the details of how the CHOOZ experiment changes when restricted to limits on matter parameters.)

However, the presence of light SM-singlet states in the theory seems to be necessary for naturalness [14], and so we should also consider the effects on these states in oscillations. Indeed, medium effects can improve the fit of four-neutrino scenarios. The medium dependence of the

light mass eigenstates arises most simply from changing the mass of the heavy dominantly singlet mass eigenstates.

The principal limitation on four-neutrino scenarios in the region near  $0.1 \text{eV}^2$  is from Bugey. Since Bugey does not constrain the matter values of the neutrino properties, but only the air, it is straightforward to reconcile LSND with the NSBL experiments. If the singlet state is  $O(0.3 \text{eV})$  in matter, but in air is much heavier and with smaller mixings, one can achieve a good fit to all existing data.

Of course, by lowering the mass of this singlet state in matter, some dominantly active mass eigenstate should also have a resulting change in its mass. From the LSND result, we expect some mass splitting to change in matter by an amount

$$\Delta m^2 > \sin^2 \theta_{\text{LSND}} \delta m_{\text{LSND}}^2 \gtrsim 3 \times 10^{-4} \text{eV}^2. \quad (5)$$

This scale suggests that the scenario is very interesting for more precise studies of the differences between air and earth mass parameters, even in existing data sets. A careful study of the implications of the atmospheric neutrino data would be worthwhile to see whether it is consistent with different oscillation lengths in air and in matter. It would be interesting to see whether a general fit of the atmospheric and K2K data can constrain four independent parameters

$$\delta m_{\text{atm:air}}^2, \quad \delta m_{\text{atm:rock}}^2, \quad \sin^2 2\theta_{\text{atm:air}}, \quad \sin^2 2\theta_{\text{atm:rock}} \quad (6)$$

describing  $\nu_\mu - \nu_\tau$  oscillations.

A broad set of possibilities exists where the details of the solar neutrinos are affected considerably, and more detailed investigations are underway [40].

#### IV. CONCLUSIONS

Although neutrino mass and dark energy are both established elements of modern physics, the origin of both is unknown. Indeed, many of the properties and interactions of neutrinos remain undetermined, as are the existence and properties of new dark particles. Neutrinos could be significantly affected by interactions with the dark sector which are sub-gravitational in strength to other visible matter. Such interactions can make the neutrino mass a dynamical quantity, depending on the environment, as well as altering the BBN and supernovae constraints on neutrino mixing, and cosmological limits on neutrino mass.

We have demonstrated that sub-gravitational strength matter-neutrino interactions can affect our interpretation of neutrino oscillation experiments, as well as absolute measurements of neutrino mass, such as neutrinoless double beta decay and tritium endpoint experiments. For instance, such effects could improve the agreement of LSND with other experiments. Although the mass splittings which account for the atmospheric, solar, K2K

and KamLAND experiments apparently indicate near degeneracy of the three known neutrinos, this degeneracy may depend on the propagation medium for neutrinos. Additional short baseline experiments will provide important tests for MaVaNs, and may directly probe the physics of the cosmological dark energy. Future neutrino experiments should be designed and analyzed with the possibility in mind of matter density dependent neutrino oscillations.

### Acknowledgments

The authors would like to acknowledge Hamish Robert-

son, Rob Fardon, Wick Haxton, Jeff Wilkes, and Kathryn Zurek for useful conversations, André de Gouvêa for reading various drafts and giving very useful suggestions, and correspondence and discussions on the attributes of many experiments with Bill Louis, Janet Conrad, Giorgio Gratta, Kate Scholberg, Richard Steinberg, Felix Boehm, Guido Drexlin, Stuart Freedman, Ed Kearns, Chris Walter and Jean Favier. This work was partially supported by the DOE under contract DE-FGO3-96-ER40956 and DE-FGO3-00ER41132.

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- [1] L. Wolfenstein, Phys. Rev. **D17**, 2369 (1978).
  - [2] S. P. Mikheev and A. Y. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985).
  - [3] S. P. Mikheev and A. Y. Smirnov, Nuovo Cim. **C9**, 17 (1986).
  - [4] M. B. Smy (Super-Kamiokande), Nucl. Phys. Proc. Suppl. **118**, 25 (2003), hep-ex/0208004.
  - [5] R. J. Wilkes (K2K), ECONF **C020805**, TTH02 (2002), hep-ex/0212035.
  - [6] A. L. Hallin et al., Nucl. Phys. Proc. Suppl. **118**, 3 (2003).
  - [7] K. Eguchi et al. (KamLAND), Phys. Rev. Lett. **90**, 021802 (2003), hep-ex/0212021.
  - [8] W. Hampel et al. (GALLEX), Phys. Lett. **B447**, 127 (1999).
  - [9] M. Altmann et al. (GNO), Phys. Lett. **B490**, 16 (2000), hep-ex/0006034.
  - [10] J. N. Abdurashitov et al. (SAGE), J. Exp. Theor. Phys. **95**, 181 (2002), astro-ph/0204245.
  - [11] B. T. Cleveland et al., Astrophys. J. **496**, 505 (1998).
  - [12] R. S. M. Gell-Mann, P. Ramond, *Supergravity*, F. van Nieuwenhuizen and D. Freedman eds. (North-Holland, 1979).
  - [13] T. Yanagida, *Proc. of the workshop on the unified Theory and Baryon Number in the Universe*, O. Sawada and A. Sugamoto eds. (KEK, 1979).
  - [14] R. Fardon, A. E. Nelson, and N. Weiner (2003), astro-ph/0309800.
  - [15] X. J. Bi, P. h. Gu, X. l. Wang and X. m. Zhang, arXiv:hep-ph/0311022.
  - [16] P. Q. Hung and H. Pas, arXiv:astro-ph/0311131.
  - [17] R. Barbieri and A. Dolgov, Phys. Lett. **B237**, 440 (1990).
  - [18] K. Kainulainen, Phys. Lett. **B244**, 191 (1990).
  - [19] G. R. Dvali and Y. Nir, JHEP **10**, 014 (1998), hep-ph/9810257.
  - [20] E. G. Adelberger, B. R. Heckel, and A. E. Nelson (2003), hep-ph/0307284.
  - [21] Y. Su, B. R. Heckel, E. G. Adelberger, J. H. Gundlach, M. Harris, G. L. Smith and H. E. Swanson, Phys. Rev. D **50** (1994) 3614.
  - [22] G. L. Smith, C. D. Hoyle, J. H. Gundlach, E. G. Adelberger, B. R. Heckel and H. E. Swanson, Phys. Rev. D **61**, 022001 (2000).
  - [23] R. F. Sawyer, Phys. Lett. B **448**, 174 (1999) [arXiv:hep-ph/9809348].
  - [24] J. W. F. Valle, Phys. Lett. **B199**, 432 (1987).
  - [25] E. Roulet, Phys. Rev. **D44**, 935 (1991).
  - [26] M. M. Guzzo, H. Nunokawa, O. L. G. Peres, V. Pleitez, and R. Zukanovich Funchal (1999), hep-ph/9908308.
  - [27] T. Ota, J. Sato, and N.-a. Yamashita, Phys. Rev. **D65**, 093015 (2002), hep-ph/0112329.
  - [28] A. S. Joshipura and S. Mohanty (2003), hep-ph/0310210.
  - [29] S. Davidson, C. Pena-Garay, N. Rius, and A. Santamaria, JHEP **03**, 011 (2003), hep-ph/0302093.
  - [30] M. Garbutt and B. H. J. McKellar (2003), hep-ph/0308111.
  - [31] M. Campanelli and A. Romanino, J. Phys. **G29**, 1861 (2003).
  - [32] K. Hagiwara *et al.* [Particle Data Group Collaboration], Phys. Rev. D **66**, 010001 (2002).
  - [33] T. Schwetz (2003), hep-ph/0311217.
  - [34] M. Sorel, J. Conrad, and M. Shaevitz (2003), hep-ph/0305255.
  - [35] M. Abbes *et al.*, Nucl. Instrum. Meth. A **374**, 164 (1996).
  - [36] J. Favier, private communication.
  - [37] F. Boehm, private communication.
  - [38] Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Lett. B **467**, 185 (1999) [arXiv:hep-ex/9908049].
  - [39] D. Steinberg, private communication.
  - [40] R. Fardon, D. Kaplan, A. Nelson, N. Weiner, and K. Zurek (2004).